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PYRHELIOMETER CALIBRATION PROGRAM OF THE U. S. WEATHER BUREAU

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ABSTRACT

A new system developed for calibrating the horizontal incidence pyrheliometer is described. The pyrheliometers to be calibrated are exposed simultaneously with a standard pyrheliometer in an integrating sphere. Calibrations are made by comparing voltages developed by the instruments undergoing calibration with those of the standard pyrheliometer. Calibration of the standard pyrheliometer is based on comparisons with the Smithsonian Institution pyranometer, both out-of-doors on clear days and within the integrating sphere. Advantages of the new system include reproducibility of the calibration within less than one percent. This is due to the reproducibility of the radiation field in the integrating sphere, in which there are relatively small variations in ambient temperature. The calibrations can be done much more rapidly and accurately than was formerly the case when the work was done out-of-doors; clear skies and minimum atmospheric pollution were necessary conditions previously.

CONTENTS

INTRODUCTION

The purpose of this paper is to describe a new system of calibrating the horizontal surface pyrheliometer. In order to show the historical continuity of the radiation activities of the Weather Bureau, a description and analysis of the previous calibration procedures are given.

For some time prior to 1952 the need for improvement in the procedures for calibration of the horizontal surface pyrheliometer was becoming acute as the radiation network expanded. In the summer of that year the Instrument Division and Scientific Services Division of the Bureau reviewed the calibration procedures then in use, with the object of improving them before beginning a recalibration program for all Weather Bureau horizontal surface pyrheliometers.

The horizontal surface pyrheliometer used by the Weather Bureau, originally designed by Kimball and Hobbs [1] and now universally known as the Eppley pyrheliometer after the manufacturer, has been calibrated in the past by indirect reference to the Smithsonian water-flow normal-incidence pyrheliometer [2].

OLD CALIBRATION SYSTEM

LINKAGE OF CALIBRATION OF FIELD PYRHELIOMETERS TO WATER-FLOW PYRHELIOMETERS

The old calibration process involved a series of steps as follows:

1. By the Smithsonian Institution: (a) Absolute cali-

bration of the water-flow normal-incidence pyrheliometer [2]. (b) Calibration of the Smithsonian Institution silver-disk pyrheliometer by direct comparison with the water-flow pyrheliometer [3, 4, 5].

2. By the Smithsonian Institution and Weather Bureau jointly: Calibration of a Weather Bureau silver-disk pyrheliometer against the Smithsonian Institution silver-disk pyrheliometer.
3. By the Weather Bureau: Calibration [6] of a standard Eppley horizontal surface pyrheliometer against the Weather Bureau silver-disk, for use by the manufacturer of the Eppley in calibration of pyrheliometers.
4. By the manufacturer: Calibration of the instruments used by the Weather Bureau in its field network, by comparison with the standard horizontal surface Eppley calibrated by the Weather Bureau for that purpose.

ERROR SOURCES

In order to determine how best to improve the calibration process, the precision of the above steps was examined. The essential facts are: The water-flow pyrheliometer of the Smithsonian Institution has long been the fundamental standard of pyrheliometry in the United States, and seems to be regarded generally as being at least as good as any other existing instrument for the measurement of flux density at normal incidence to the sun. In several European countries the standard of pyrheliometry is the Ångström pyrheliometer, an instrument based on physical principles different from those of the water-flow. Comparisons have been made indirectly between the two standards. The results indicate that the standards are in close agreement. Ångström [7] indicates that the two can be reconciled within 0.1 percent. No further examination of the water-flow will be made here. The question of "pyrheliometric scale" is treated in a final paragraph.

Calibration of the Smithsonian silver-disk pyrheliometer against the water-flow is reproducible with an accuracy of the order of a tenth of 1 percent. Data are shown in table 1, the source being page 7 of [5].

Calibration of the Weather Bureau silver-disk No. 1 against the Smithsonian silver-disk pyrheliometer (No. A. P. O. 8 bis) is of the same order of accuracy as that of the Smithsonian silver-disk against the water-flow—about one-tenth of 1 percent. Data kindly supplied by Mr. Aldrich of the Smithsonian Institution are shown in table 2.

TABLE 1.—*A summary of all comparisons between S. I. 5 bis and standard water-flow pyrheliometer No. 5.* (*Source: p. 7 of* [5])

No. of values	Date	Mean constant
37	1932	0.3625
42	1934	.3629
18	1947	.3626
100	1952	.3622
Mean		.36255

Average deviation from mean ±0.055 percent.

TABLE 2.—*Calibration of Weather Bureau silver-disk pyrheliometer No. 1 against Smithsonian Institution silver-disk pyrheliometer A. P. O. 8 bis.* (*Source: data supplied by Mr. Lyle B. Aldrich of the Smithsonian Institution.*)

No. of values	Date	Mean constant
8	June 3, 1930	0.3714
8	April 20, 1931	.3700
8	April 4, 1932	.3703
8	March 15, 1934	.3704
17	September 25 and 26, 1936	.3717
16	October 23, 1940*	.3720
11	January 8, 1942	.3731
24	April 27, 1945	.3742
24	October 16, 1948	.3729

*In October 1940 new mercury was inserted in S. I. 1 and the silver disk reblackened.

TABLE 3.—*Extreme variation about its mean calibration for each of a set of standard Eppley pyrheliometers.* (*Source of basic data: Mr. Hedley Greer of Eppley Laboratories.*)

Standard Eppley pyrheliometer no.	Difference between extreme calibrations as a percent of the mean
395	7
389	7
245	8
362	4
489	5
1822	4

The standard Eppley pyrheliometer is calibrated against the Weather Bureau silver-disk as described in [6]. Some information on the accuracy of the results of this process is obtainable indirectly from an analysis of the calibration constants obtained over a period of years for the standard pyrheliometers. Data for six instruments indicate an average deviation about the mean of ±2 percent. Extreme variations (highest value minus lowest value divided by the mean of the constant of the individual instrument) for each of six pyrheliometers are shown in table 3. Time series graphs of the constants of five pyrheliometers are shown in figure 1. (Data on which this figure is based were kindly provided by Eppley Laboratories, Inc.)

It was originally assumed that variations in the constant of a pyrheliometer with time arose from substantial changes in the instrument. However, in view of the apparent random nature of the variations shown in figure 1, it appears that such an assumption is questionable, and that the changes may well have been associated with circumstances of the calibration process, such as ambient temperature, rather than with actual changes in the pyrheliometers.

It is difficult to obtain data on the error involved in calibration of the instruments actually used in the field against the standard pyrheliometer. For example, data showing calibration of one pyrheliometer against a particular standard over a series of years are not available. We are forced to consider indirect evidence.

Calibration constants for a set of 12 pyrheliometers called in from the field for recalibration and calibrated originally by the manufacturer against the same standard Eppley (the calibration constant of which had remained unchanged during the period of calibration of the 12 field

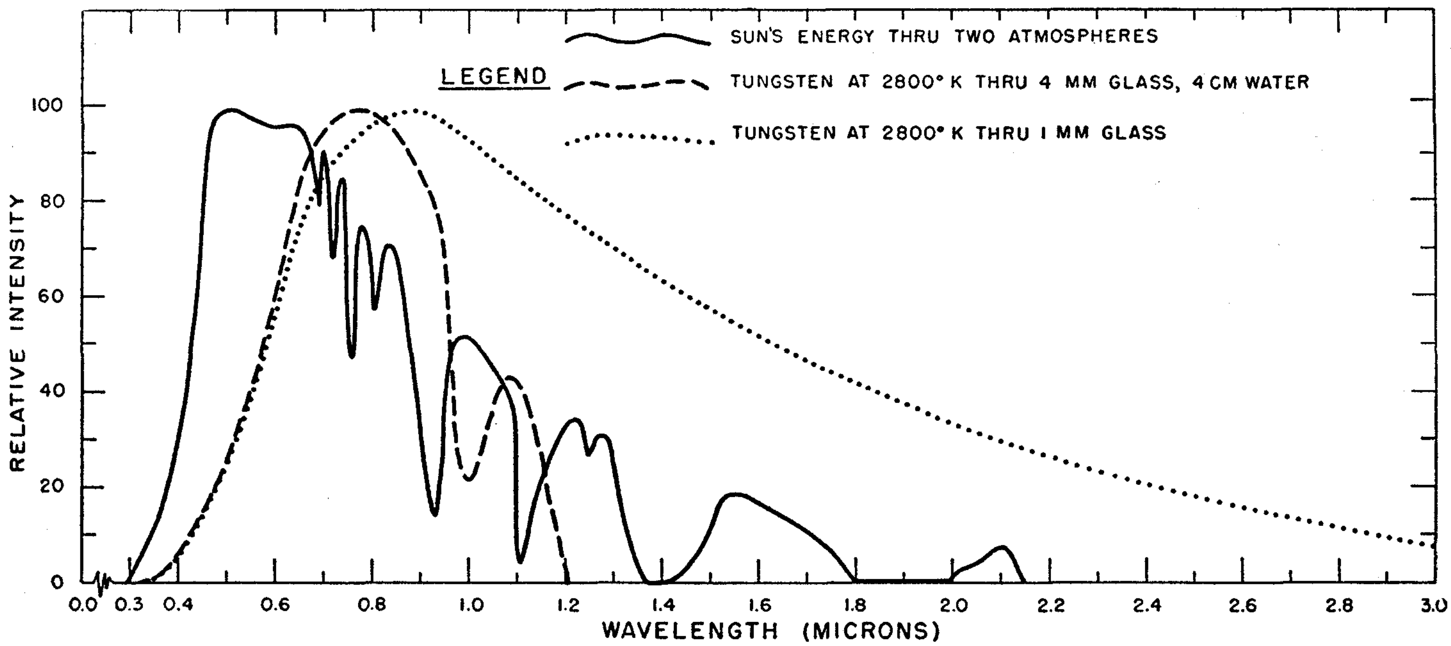

FIGURE 1.—Time series of calibration constants of five standard pyrheliometers. (Data from Eppley Laboratories, Inc.)

TABLE 4.—*Comparison of original calibration constants with laboratory constants*

Pyrheliometer serial No.	Original calibration constant	Integrating sphere calibration constant (c. c.)	Fractional deviation of original c. c.	"Random Error"*
1574	2.13	2.12	−0.00	+0.043
1689	2.07	2.13	−.03	+.013
1693	2.09	2.14	−.02	+.023
1719	2.29	2.44	−.06	−.017
1720	2.20	2.34	−.06	−.017
1759	2.34	2.53	−.07	−.027
1772	2.37	2.57	−.08	−.037
1793	2.38	2.48	−.04	+.003
1799	2.45	2.41	+.02	+.063
1805	2.22	2.36	−.06	−.017
2273	2.40	2.57	−.07	−.027
Mean			−.043	.000
Mean of absolute value				.026

*The "random error" is here obtained by adding 0.043 to the individual values in the preceding column. −0.043 is the mean of the fractional deviations.

TABLE 5.—*Uncertainty in the steps of the old calibration system*

Step	Method of determining degree of uncertainty	Approximate uncertainty percent
Calibration of water-flow	Indirect comparison with European standard.	0.1
Smithsonian silver-disk vs. water-flow	Average deviation about mean calibration.	.055
Weather Bureau silver-disk vs. Smithosnian silver-disk.	do	0.1
Standard Eppley vs. Weather Bureau silver-disk.	do	2
Field instruments vs. standard Eppley	do	4

pyrheliometers) can be compared with the calibrations recently obtained for the same set of instruments under laboratory conditions to be described. Results are shown in table 4. These data indicate that the original calibrations of the set were systematically about 4 percent low, and that there was a random component of error amounting to about 3 percent. (If the calibration constant is too low, indicated radiation is too high.)

The information outlined above is summarized in table 5. No precise or elaborate statistical treatment is needed to show the relative importance of the several error sources in the calibration chain connecting the water-flow standard to calibration of the Eppley pyrheliometers used in our field network. The brief examination above indicates clearly that improvement in the process should begin with the calibration of the standard Eppley, and should include calibration of the field pyrheliometers against the standard Eppley.

DETAILS OF OLD METHOD OF CALIBRATING EPPLEY STANDARD AND FIELD PYRHELIOMETERS

In the old calibration process, the standard Eppley (which measures flux density Q on a horizontal surface from the entire hemisphere of the sky) was calibrated against the Weather Bureau silver-disk (which measures flux density N from the sun, on a surface normal to the sun's direction). We designate the e. m. f. generated by the Eppley in measuring Q as e_q. The Eppley can also be used to measure the diffuse sky radiation flux density D on a horizontal surface by shading the pyrheliometer from the direct sun by means of a shade-ring or disk [6]. The e. m. f. of the Eppley when measuring D will be written e_d.

Calibration of the Eppley against the silver-disk is done by recording e_q and e_d alternately over a short time interval during which N is also measured, during a day having cloudless skies. The calibration constant C, in millivolts/langleys* per minute, is computed from

$$C = \frac{(e_q - e_d)/\cos i}{N}$$

where i is angle of incidence.

*One langley is 1 gram calorie per square centimeter.

Calibration of the field pyrheliometer against the standard Eppley (the standard being one calibrated by the Weather Bureau as just described) was done by exposing both instruments on a clear day to sun and sky, and obtaining simultaneous records of the outputs of each by means of either a portable potentiometer or recording potentiometer. This was done on a day or a set of days selected for low atmospheric pollution as judged by visibility, haziness, pyrheliometer recordings, etc.

In both of these steps (i. e., calibration of the Eppley standard, and calibration of the field pyrheliometers) the results depended to some extent on effects of angle of incidence, ambient temperature, and atmospheric pollution. The first two of these effects are known, for example, from [8]. That the degree of atmospheric pollution existing at the time of calibration is a factor in the calibration can be seen from the following: Whereas with no pollution there is a minimum of solar radiation scattered from the angular area immediately surrounding the sun, in the presence of pollution there is considerable scattering. Further, the intensity of this scattered radiation varies markedly with angular distance from the sun. Therefore, under conditions of pollution the degree to which the silver-disk "sees" the same flux as the horizontal-surface pyrheliometer being calibrated depends on the precision with which the angular area presented by the shade ring or disk matches the angular area irradiating the silver-disk pyrheliometer. Also, with pollution, the geometry of the normal-incidence pyrheliometer becomes pertinent [9, 10]. Further, in the presence of appreciable atmospheric pollution the flux density is likely to vary rapidly with time, in a random fashion; possible differences in time constants of the two instruments gives rise to additional uncertainty in the calibrations.

DEVELOPMENT OF NEW CALIBRATION PROCEDURE

It is apparent, then, that ambient temperature, angle of incidence, and degree of pollution all exert some effect on the calibration obtained for the standard Eppley, and that in general to every set of these three elements there corresponds a calibration constant. The magnitude of the effects of angle of incidence and temperature are shown in [8], but we have not measured the magnitude of the pollution effect. A new calibration procedure should take account of these elements in the calibration of the Eppley standard and in calibration of the pyrheliometers used in the radiation network. The two phases of the process are treated here as separate problems.

THE PYRANOMETER AS A STANDARD

On May 3, 1952, the authors outlined the project to Mr. L. B. Aldrich and the late Mr. W. H. Hoover, of the Smithsonian Institution, and requested their advice on the problem of improving the calibration of the standard Eppley. Their reply stressed the adverse effects of the shade-rings. They suggested that a substantial improvement in precision of calibrating the standard Eppley could be expected through the use of the Smithsonian pyranometer [11, 12], and gave convincing arguments to that effect.

The pyranometer is a compensation-type pyrheliometer which can be exposed to measure normal-incidence flux density when shielded from sky radiation by means of an apertured tube such as is used on the silver-disk and water-flow. The instrument can also be used to measure total solar and sky radiation on a horizontal surface by removing the tube. It is equipped with a precision-ground hemispherical quartz envelope of uniform thickness. The tube is constructed with the object that the angular area about the sun "seen" by the instrument when measuring only direct solar radiation should match as closely as possible that of the silver-disk against which it is calibrated.

An examination of the data on calibration of the pyranometer against the Smithsonian silver-disk at Mount Wilson at normal incidence, kindly supplied by Mr. Aldrich, showed a mean deviation from average calibration amounting to about 0.2 percent of the mean calibration. Table 6 contains calibration data for the pyranometer.

TABLE 6.—*Calibrations of pyranometer no. 14 against silver-disk A. P. O. 8 bis. (Basic data source: Mr. Aldrich, Smithsonian Institution)*

Date	Number of comparisons	Mean constant	Deviation from mean
May 7, 1952, a. m.	8	18.485	0.025
May 7, 1952, p. m.	8	18.468	.008
May 7, 1952, p. m.	6	18.465	.005
May 15, 1952, p. m.	4	18.462	.002
May 27, 1952, a. m.	8	18.451	.009
May 27, 1952, p. m.	8	18.505	.045
May 27, 1952, p. m.	8	18.506	.046
June 2, 1952, a. m.	8	18.491	.031
June 3, 1952, a. m.	8	18.451	.009
July 13, 1952, a. m.	10	18.403	.057
July 14, 1952, a. m.	9	18.492	.032
July 14, 1952, a. m.	10	18.335	.125
July 14, 1952, p. m.	6	18.478	.018
July 15, 1952, a. m.	10	18.452	.008
July 15, 1952, p. m.	10	18.431	.029
April 7, 1953, a. m.	6	18.493	.033
Mean		18.460	.030

.030/18.460 equals about $2(10^{-3})$

It was decided then to accept the advice of Mr. Aldrich and Mr. Hoover, and to take advantage of their kind offer to cooperate in our program by furnishing and operating the pyranometer, and a procedure for calibration of a standard Eppley against the pyranometer was arranged.

CALIBRATION OF THE STANDARD EPPLEY AGAINST THE PYRANOMETER

The requirements that the radiation field and ambient temperature be standardized and pollution effects suppressed in the calibration process suggest that laboratory processes are desirable. Early in the study of the problem, it appeared that the use of a radiation integrating sphere would provide a solution since the great precision in measurement of distances generally involved in optical-bench setups is not necessary in the integrating sphere. The uniform flux density constituting the radiation field in the sphere is desirable since possible directional effects due to small irregularities in the glass envelope and detector sensitive surface are integrated. Ambient temperature varies over but a small range since the sphere is in a well-insulated building; and pollution effects are eliminated. The authors decided to carry out a program of calibration of a standard Eppley out-of-doors under clear-sky conditions on days of minimum pollution and to compare the results with calibrations of the same Eppley, against the pyranometer, in an integrating sphere. An excellent integrating sphere located at the National Bureau of Standards, Washington, D. C., was found to be available.

Calibration with sun as source.—Through the good offices of Dr. W. F. Shenton, head of the mathematics department of American University, Washington, D. C., permission for use of the attic and roof of Hurst Hall on the university campus was kindly granted by the president of the university, Dr. H. R. Anderson. The exposure there is one of the best available in the Washington area, being almost completely free from obstructions to the nearly flat horizon, and having relatively few important local sources of atmospheric pollution. Six Eppleys were installed on the roof and leads were run down a ventilating shaft to the attic in which the auxiliary measuring apparatus was installed. Mr. Aldrich and Mr. Hoover, who handled all details of the pyranometer work, installed the pyranometer within about 2 feet of the center of the cluster of pyrheliometers. Their auxiliary measuring equipment was also installed in the attic. Since one of the pyrheliometers exposed (No. 1973) previously had been subjected to numerous tests to determine its characteristics, it was chosen to be the standard. The others were exposed to provide a margin against damage to No. 1973.

Operation of the pyranometer requires that the detector unit be exposed to the sun for 20 seconds by the flipping open of a solenoid-operated lid and that the immediate deflection of a ballistic-type galvanometer be read. The lid is then closed and electric power is metered to a strip of the detector in quantity sufficient to produce a galvanometer deflection matching that observed when the unit was exposed to sun and sky. The observer then records the current, as read from a suitable meter. (Full details of the pyranometer are given in [11, 12].) To coincide with an observation made with the pyranometer, a reading of the pyrheliometer was made at the instant the lid to the pyranometer was flipped open. A system of buzzers made it possible to synchronize the observations of pyranometer and pyrheliometers satisfactorily. Buzzer and solenoid were controlled automatically by timing switches. Two observers operated thermocouple switches to connect the pyrheliometers to portable potentiometers. Each observer began a series of readings on the three pyrheliometers assigned to him when the buzzer signaled that the pyranometer lid had opened. The sequence of reading of the pyrheliometer voltages was reversed by each observer on each successive calibration to avoid having a systematic time displacement between any of the pyrheliometer readings and those of the pyranometer. A series of readings was taken every 2½ minutes. It took an observer about 40 seconds to read the 3 pyrheliometers. Readings were taken both in the forenoon and afternoon.

Readings of ambient temperature were obtained by means of a resistance thermometer, the sensing element of which was shielded from the sun and mounted among the pyrheliometers. A wheatstone bridge unit, connected to the thermometer element, was mounted near one of the portable potentiometers in the attic.

When these arrangements had been completed, a day of clear weather, with a level of atmospheric pollution as low as might be expected in any reasonable length of time, was awaited. Such a day occurred on August 25, 1952, and the first measurements were made then. On that date 97 calibration sequences were taken, spanning a range of solar elevations from 62° to 24°. The following day was also suitable and 106 sequences were taken spanning solar elevations from 61° to 24°. Other observations were obtained on January 26 and February 9, 1953, but the elevation angles were so small that the data were of only secondary importance; e. g., testing temperature effects. Processing of data consisted of the following steps for each sequence:

1. Tabulation of Eastern Standard Time of the beginning of the sequence.
2. Computation and tabulation of the corresponding apparent solar time.
3. Computation and tabulation of solar altitude.
4. Tabulation of the voltage output for each of the pyrheliometers.
5. Tabulation of the corresponding flux density measured by the pyranometer.
6. Determination of the calibration constants by dividing millivolts output by flux density to obtain millivolts/langleys per minute.
7. Tabulation of ambient temperature.

The above provided the desired fundamental data. Various studies were made attempting to reconcile laboratory data on cosine response and ambient temperature with similar data obtained in the calibrations at American University—"sun calibrations". These were not entirely successful, and indicated the possibility of a cosine-response effect in the pyranometer and suggested the form and amount. Subsequent tests on the pyranometer at the Smithsonian Institution did not bear out the details of the suggested cosine curve, but did indicate that there was a small cosine effect in the pyranometer and that the best results in calibrating the Eppley against the pyranometer using the sun as source could be expected at low values of angle of incidence, corresponding to those at which the pyranometer had been calibrated against the silver-disk. Accordingly, to represent the sun calibration of Eppley standard No. 1973, an average calibration over the angle-of-incidence interval 28° to 60° (28° being the smallest angle of incidence at which data were obtained, and the span 28° to 60° being an interval of nearly constant small slope in the cosine curve) was computed as representative of the constant for the midpoint of that interval—i. e., angle of incidence 44°. As mentioned, these data were obtained on August 25 and 26, 1952. Temperature conditions during the two days were quite similar. Average ambient temperature was about 75° F. (While [8] shows that the temperature effect is not quite linear, departure from linearity introduces no more than a trivial difference from the mean temperature obtained by an arithmetic averaging.) The calibration figure obtained is:

Pyrheliometer No	1973.
Calibration Constant (millivolts/langleys per minute)	2.40.
Angle of incidence	44.
Ambient temperature	75° F.

Calibration in the integrating sphere.—While the calibrations were being carried out at American University, arrangements were made for carrying out calibration work at the National Bureau of Standards integrating sphere, through the generous cooperation of Mr. Ray Teele, of the Radiometry Section of the Division of Optics, in the Materials Testing Building of the National Bureau of Standards in Washington, D. C.

The integrating sphere (see [13] for theory) is about 15 feet in diameter. It is arranged with hinges and casters to open along a vertical diametrical plane, giving ready access to the interior. The walls of the interior are painted with a special highly reflective magnesium oxide paint. The radiation source is a tungsten-in-glass lamp of 2,500 watts, the voltage to which was controlled during our operations by means of a variable transformer, spanned by an accurate a. c. voltmeter. Temperature of the filament was estimated by Mr. Teele as about 2,800° K.

On two separate occasions (March 23, 1953, and April 1, 1953) the pyranometer and pyrheliometer No. 1973 were set up in the integrating sphere. Calibrations obtained were 2.343 and 2.334, respectively, at ambient temperatures 85°–90° F. The mean of these calibrations is 2.34 to the nearest hundredth. This figure can be corrected to ambient temperature 75° F. by reference to data in [8]; the resulting constant is 2.36. Summarizing,

	millivolts/langleys per minute
Out of doors at American University, calibration at ambient temperature 75° F	2.40
Integrating sphere: calibration, reduced to 75° F	2.36

These values disagree by about 1.7 percent.

DISCUSSION OF RESULTS

The difference of 1.7 percent in the calibrations obtained in the integrating sphere and out of doors requires comment. Conditions in the integrating sphere differ in two essential respects from those existing at American University during the work there. They are (1) the spectral distribution of radiation from the radiation source (sun and sky at American University vs. the 2,800° K. incandescent tungsten-in-glass lamp in the integrating sphere), and (2) radiation "field" (uniform diffuse flux density in the sphere vs. largely unidirectional radiation from an angle of incidence varying from 22° to 65° at American University).

If the pyrheliometer and pyranometer differ with respect to spectral response over the intervals of the spectrum involved in the two tests, the results might be reflected in a discrepancy between the calibrations of the pyrheliometer obtained in those tests. An experiment performed in the laboratory (described in the appendix) indicated that such an effect would influence the calibration by not more than about one-tenth of one percent. Evidently the observed discrepancy of 1.7 percent cannot be ascribed to spectral considerations.

Differences in the radiation field can influence the calibration of the pyrheliometer due to the differing cosine response characteristics of the two instruments. If sufficiently comprehensive data were available for both instruments, it would be possible to compute the magnitude of the effect and so verify the hypothesis that the discrepancy arises from cosine characteristics. This would require data for angles of incidence and azimuth corresponding to the solar paths "seen" by each instrument during the tests since, especially in the pyrheliometer, there is a small random variation in calibration with azimuth as well as angle of incidence. It hardly seems feasible to do this at present. The cosine response data available for the pyrheliometer suggest that the integrator calibration should be slightly lower than the out-of-doors calibration and it is believed likely that a large part of the 1.7-percent discrepancy arises from the pyrheliometer cosine characteristic and cannot be suppressed without substantial (and probably expensive) improvements in the pyrheliometer.

The question now arises as to which calibration to assign the instrument. In the aggregate, it seems likely that more record will be taken with the sun obscured by clouds than with the sky clear and the sun near 45° (or any other specified) angle of incidence. The former condition corresponds very roughly to the sphere calibration conditions, the latter to the American University calibrations. On this basis, calibration under the diffuse radiation of the integrating sphere calibration seems preferable and is taken as definitive. An analysis of the cosine response of pyreheliometer No. 1973 together with the Moon-Spencer [14] cloudy-sky radiation distribution also indicates the sphere calibration is preferable for cloudy-sky conditions.

CALIBRATION OF FIELD PYRHELIOMETERS AGAINST THE STANDARD EPPLEY

Use of the integrating sphere makes it possible for two men to easily calibrate a dozen pyrheliometers in a day against the standard Eppley. Experience to date on about 50 pyrheliometers has shown that without exception the calibration is reproducible to better than one percent accuracy.

THE QUESTION OF PYRHELIOMETRIC SCALE

The concept of "pyrheliometric scale" arises in the following way. The water-flow pyrheliometer [2] was established in the period 1910 to 1913 as the standard pyrheliometer by the Smithsonian Institution. From time to time since then, improvements have been made in the water-flow pyrheliometer, each of which led to an estimation of the systematic error involved in previous measurements with the water-flow and hence of instruments calibrated against it, directly or indirectly. However, in order that measurements with field instruments should be kept comparable over the years, in general, this systematic error, while recognized, was not corrected for in the field measurements. This has proved to be a sound policy, in view of the several changes in "scale" which would otherwise have greatly complicated comparisons of observations over a period of years.

The Weather Bureau has observed such a policy in its field measurements [6, p. 418], and while there are several arguments pro and con on the problem of changing to a basis eliminating all known systematic error insofar as possible, the policy of the Weather Bureau has not been changed and for the time being at least the basis of calibration remains the "Smithsonian scale of 1913." Present opinion [5, p. 7] is that the 1913 scale is 2.5 percent too high. This indicates that field measurements calibrated to the 1913 scale give data systematically 2.5 percent too high.

SUMMARY

A system for calibrating the standard Eppley against the pyranometer has been devised and placed in effect. A new system for calibration of the pyrheliometers used in the network has also been devised and placed in effect. The latter system, which involves comparison calibrations against a standard Eppley in an integrating sphere, makes it possible for two men to calibrate a dozen pyrheliometers a day with reproducibility accurate to better than one percent. Previously, two men could calibrate only about 3 pyrheliometers a day, and then only during the rare occasions when skies were clear and atmospheric pollution at a minimum, and with repeatability of about 3 percent.

The new calibration linkage from water-flow normal-incidence pyrheliometer to field pyrheliometer is now the following:

1. By the Smithsonian Institution: (a) Absolute calibration of the water-flow normal-incidence pyrheliometer. (b) Calibration of the Smithsonian Institution silver-disk pyrheliometer by direct comparision with the water-flow pyrheliometer. (c) Calibration of the pyranometer by direct comparison with the Smithsonian silver-disk pyrheliometer.
2. By the Smithsonian Institution and Weather Bureau jointly: Calibration of the standard Eppley against the pyranometer.
3. By the Weather Bureau: Calibration of pyrheliometers used in the radiation network in the integrating sphere against the standard Eppley.

The calibrations are based on the 1913 scale, as heretofore.

APPENDIX

In the case of the calibration of the Eppley standard against the pyranometer, the method consists essentially of a determination of the flux density Q by means of the pyranometer and the millivolts e_q simultaneously generated by the Eppley, both instruments being exposed to the sun and sky. The calibration constant C is then

$$C = e_q / Q$$

A sufficient condition that a calibration under a radiation source other than sun and sky be accurate when measuring sun-and-sky radiation is that e_q/Q as determined under the calibration source should be the same as e_q/Q measured under sun-and-sky radiation source. It is desired then to determine whether e_q/Q given with the tungsten lamp as a radiation source is the same as e_q/Q with the sun as the source.

It is difficult to make a direct comparison, by attempting to obtain a calibration from the two sources at identical angles of incidence. It is very much simpler to obtain ratios by using the unfiltered tungsten lamp as a source first, and then by using the same source with a water filter, as is described in the following experiment:

The pyranometer and pyrheliometer were mounted on opposite sides of a precision turntable, above which was mounted a tungsten lamp similar to the one used in the integrating sphere and with the same voltage across its terminals. The turntable was equipped with a vernier for precisely positioning the detectors.

With the lamp turned on (power was fed through a voltage stabilizer and regulator), the pyranometer and pyrheliometer were successively placed beneath the lamp and readings taken. A water-cell filter, consisting of about one-eighth inch of glass and 4 cm. of water, was introduced into the radiation beam and readings were repeated. The calibration constants computed under the two radiation fields agreed within one-tenth of 1 percent. This indicates that the relatively large amount of radiation coming in at wavelengths greater than 1 micron from the unfiltered tungsten lamp introduces no error greater than 0.1 percent into the calibration of the pyrheliometer.

Figure 2 shows spectral distribution of radiation from the tungsten lamp, with and without the water filter, together with solar radiation spectral distribution [15]. The first two were computed from spectral distribution of radiation data for tungsten at 2,800° K. (estimated by Ray Teele as being the temperature of the tungsten lamps used during the calibration in the integrating sphere) together with liquid water transmission data [16] and trans-

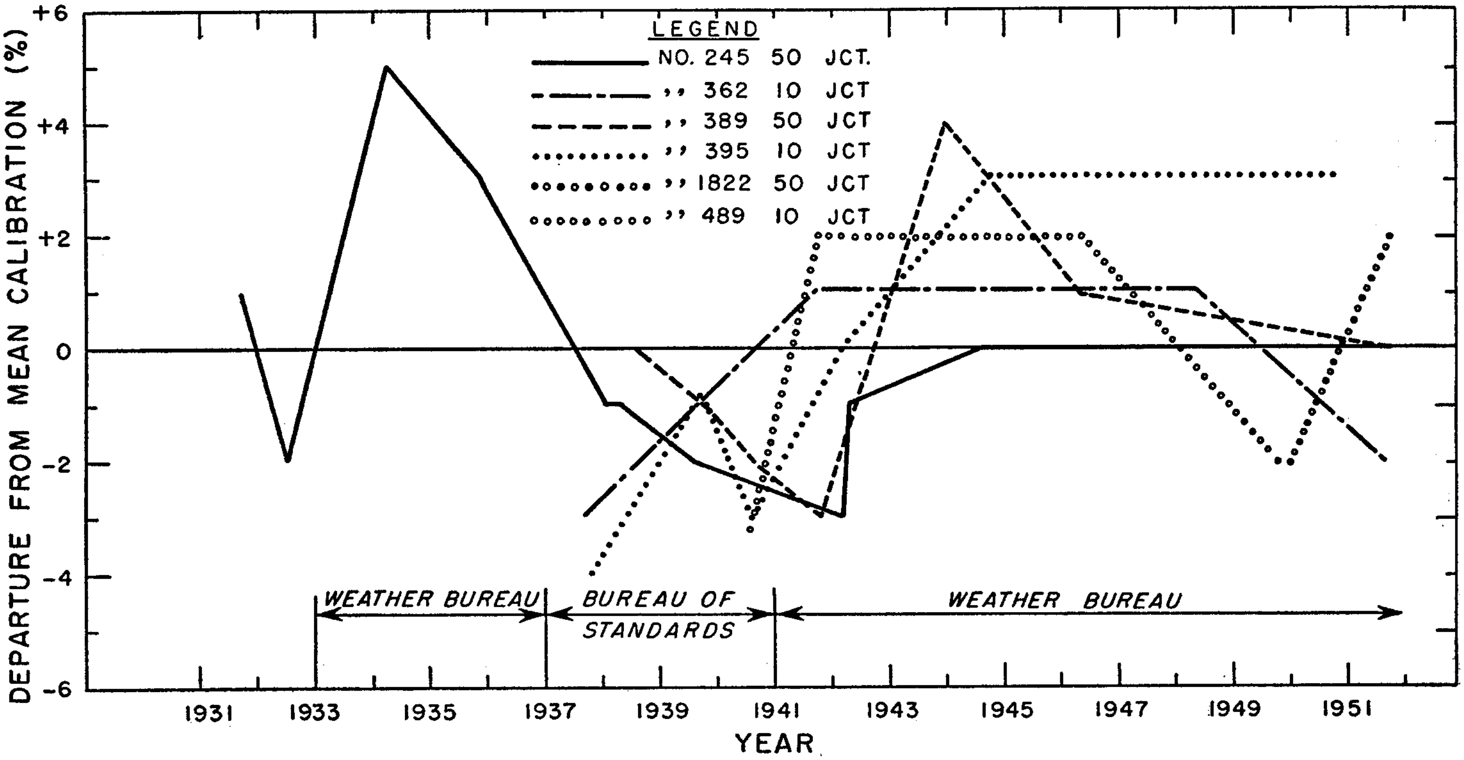

FIGURE 2.—Normalized transmission curves of solar radiation and tungsten-lamp radiation with and without the water filter.

mission data for glass.* The water cell reduces the proportion of radiation from wavelengths greater than 1 micron from 87 percent to 33 percent—i. e., from more than solar radiation amount to less than that for solar radiation.

Further examination of figure 2 shows that the introduction of the water-glass filter into the radiation beam from the tungsten filament lamp does not produce radiation matching the solar radiation, but that the tungsten is displaced somewhat to the long-wave side of the solar distribution curve. The question arises as to the possible differences in ratio of response of the pyranometer and pyrheliometer under these two slightly different spectral distributions.

The coverings of the two instruments are different. The pyranometer is covered with a quartz envelope, whereas the Eppley cover is glass. The receiving surface of the pyranometer is finely divided carbon as is the black receiving element in the Eppley. There is no surface in the pyranometer corresponding to the white receiving annular ring of the Eppley, under which the cold junctions of the thermopile are located. It appears from this that if there are differences in relative response of the pyranometer and pyrheliometer with the change in spectral distribution in question, they must arise from differences in relative transmission of the two covers, or from variations in the spectral reflectance of the white element in the Eppley, or from both.

An examination of the data indicates no measurable change in the relative transmissions of glass and quartz from 0.4 to 1 micron. Data for spectral reflection of MgO by Middleton [17] show no considerable change in spectral reflectivity of MgO in the region. It appears that the spectral effects on the calibration do not exceed about 0.1 percent.

*Glass transmission data by Corning Glass Works, National Bureau of Standards, and General Electric Co.

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